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ENERGY LOSS OF COSMIC RAYS IN THE INTERPLANETARY MEDIUM

M. L. GOLDSTEIN
L. A. FISK
R. RAMATY

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

ENERGY LOSS OF COSMIC RAYS IN THE INTERPLANETARY MEDIUM

M. L. Goldstein*, University of Maryland,

College Park, Maryland, 20742, and

L. A. Fisk+ and R. Ramaty,

NASA/Goddard Space Flight Center,

Greenbelt, Maryland, 20771

ABSTRACT

The expansion of the solar wind is likely to cause low energy cosmic ray particles to lose a significant fraction of their energy in the interplanetary medium. It is shown that because of this effect, most of the protons observed below ~ 100 MeV and alpha particles, below ~ 60 MeV/nucleon originate at higher energies, making it impossible to sample directly the interstellar spectra at these energies.

It has been shown[1,2] that cosmic ray particles lose energy in the interplanetary medium as they are scattered among magnetic irregularities moving outward with the expanding solar wind. In these treatments, the cosmic ray number density $U(r,T)$, per unit interval of kinetic energy T, satisfies a spherically-symmetric Fokker-Planck equation[1,3]

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V U\right) - \frac{1}{3}\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\right)\left(\frac{\partial}{\partial T}\left(\alpha T U\right)\right) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial U}{\partial r}\right) \tag{1}$$

which allows for the effects of convection, diffusion and energy loss. Here $\kappa(r,T)$ is the particle diffusion coefficient, $V(r)$ is the solar wind speed, and $\alpha(T) = (T + 2\,mc^2)/(T + mc^2)$, with mc^2 the rest energy of a particle.

Eq. 1 is difficult to solve analytically with all but the simplest forms of κ and U_o, the unmodulated, interstellar spectrum[4]. There have been, therefore, few attempts to determine the amount of energy cosmic ray particles are likely to lose in the interplanetary medium using values of κ and U_o which approximate the actual conditions. Some useful approximations to Eq. 1 have been developed and used for this purpose[5], but in general these approximations are not valid at energies below, say, 150-200 MeV/nucleon where energy loss processes should be extremely important. Recently, Fisk[6] has outlined a numerical technique for solving Eq. 1 which is valid at all energies, for general forms of κ, V, and U_o. In the present Letter, we shall use this technique to assess the energy lost in the interplanetary medium by cosmic rays of various interstellar energies, and we shall discuss the influence of this effect on our ability to directly determine the interstellar spectrum at low energies.

In a recent Letter[7], we compared the observed electron spectrum in 1965 with the interstellar electron spectrum inferred from the nonthermal radio background. We concluded that the modulation of electrons deduced from this technique will not yield a reasonable modulation for protons unless energy loss in the interplanetary medium was taken into account. Using the numerical technique of Fisk[6], we found that the diffusion coefficient in 1965 could be represented by $\kappa = 1.5 \times 10^{21}\ \beta\kappa_1(P)\exp\left((r-1)/1.6\right)\ \mathrm{cm^2 sec^{-1}}$, where β is particle speed in units of c, r is in units of A.U., and P is particle rigidity in units of BV; $\kappa_1(P) = P$ for $P \geq .35$ BV and $\kappa_1(P) = (.35\ P)^{1/2}$ for $P \leq .35$ BV. We shall continue to use this diffusion coefficient in the present computations, since it appears to provide an adequate description of interplanetary conditions during solar minimum, at least near the orbit of earth. For $P \geq .35$ BV, the magnitude and rigidity dependence of this diffusion coefficient is in excellent agreement with the diffusion coefficient inferred from measurements of the radial gradient of the cosmic ray intensity in 1965[8], and up to $P \sim 6$ BV (where the effects of the modulation are negligible) it is in reasonable agreement with the diffusion coefficient predicted from solar minimum measurements of the power spectrum of magnetic field fluctuations[9]. A diffusion coefficient which varies as $P^{1/2}$ rather than P at low rigidities is also in agreement with power spectra predictions[9]. The choice of the radial dependence of the diffusion coefficient, however, is somewhat more subjective. Rather than choosing the exponentially varying diffusion coefficient above, we could choose one which is constant in radial distance out to 2 - 3 A.U. and thereafter becomes infinitely large, as has been suggested by some studies of the behavior of cosmic rays during solar flare events[10]. In either case, the principle modulating region lies within a few A.U. of the Sun, and predictions of the modulation and energy losses of the particles will be essentially the same. If, however, the modulating region is much larger than we have assumed here, or if there is more modulation beyond the earth than between the earth and the Sun, then our estimates of the energy loss will be too small. In any event, our calculations can be considered to be a reasonable lower limit to the actual energy loss, since a modulating region which is smaller than the one we have assumed above would be inconsistent with the electron modulation deduced from the galactic nonthermal radio emission.[7]

We consider a series of essentially monoenergetic interstellar spectra centered at different energies T_o and we compute the resultant spectra at earth using Eq. 1 and the interplanetary parameters given above. The Fokker-Planck equation, when used to determine the differential number density in the frame fixed with respect to the Sun (as done in the present Letter), is valid for steep interstellar spectra only if $\varepsilon = \frac{V}{c\beta}\frac{\partial \ln U}{\partial \ln T} \ll 1$[3, 11].
We have chosen, therefore, input spectra of the form $U_o \propto \exp(-50\,(\ln T/T_o)^2)$ which satisfy this condition whenever the number of particles present is numerically significant.

The results are shown in Figures 1 and 2 for protons and alpha particles, respectively. The solid curves represent the various input interstellar spectra and the light dashed curves are the corresponding modulated spectra at earth. The normalization of the input spectra was chosen so that their upper envelope is a power law in total energy. The heavy dashed curve represents the sum of the all light dashed curves.

As can be seen, at high energies (curves 9 and 10) the effects of the modulation are negligible. At lower energies, in addition to a net suppression due to diffusion and convection, the effects of energy loss become evident. Down to an energy of several hundred MeV (curve 6) a mean energy loss, as represented by the displacement between the peaks of the modulated and unmodulated spectra, is a useful quantity and can be estimated from Gleeson and Axford's[5] formula for the mean energy loss, ϕ:

$$\phi \cong \frac{\alpha T}{3} \int_r^\infty \frac{V dr'}{K} = 210 \text{ Mev} \tag{2}$$

using the diffusion coefficient given above. At lower energies (curves 5 and below) the spread in the modulated spectra is so large that a mean energy loss is no longer a meaningful concept.

The most striking feature which results from the energy loss is that below ~ 100 MeV for protons and ~ 60 MeV/nucleon for alpha particles the modulated spectra become virtually insensitive to the interstellar spectra in the same energy regions. At these energies, the heavy dashed lines are comprised almost entirely of curves 4 and 5 for protons and 3 and 4 for alpha particles, all of which originiate at higher energies. The degree to which the low energy spectra at earth are insensitive to variations in the interstellar spectrum can be seen from the fact that curve 2 for protons, and curve 1 for alphas, could be increased by more than 2 orders of magnitude without significantly modifying the observed spectra.

In our previous study[7], we found that, with the diffusion coefficient given above, a reasonable fit to the proton data in 1965 could be obtained by choosing the interstellar intensity to be a power law in total energy. This result is shown in Figure 3 together with an alpha particle spectrum at earth that was also obtained using an interstellar intensity which is a power law in total energy per nucleon. This choice of the interstellar alpha particle spectrum gives a good fit to the observed alpha particles, and is consistent with an energy independent proton-to-alpha ratio in interstellar space. This latter statement, however, can be safely made only for energies greater than ~ 100 MeV/nucleon. Below this energy, as demonstrated above, the energy loss prohibits us from directly sampling at the earth the interstellar particles.

In conclusion, because of the energy loss resulting from the expansion of the solar wind, it is not possible to determine the interstellar particle spectra at low energies from direct cosmic ray measurements at earth, even if the modulation mechanism were completely understood and the relevant parameters known. For this reason, we cannot determine, for example, whether there is a sufficient number of low energy cosmic rays to heat the interstellar medium, i.e., significantly more than is predicted by a power law in total energy which was found to be inadequate for this purpose[12]. On the other hand, energy losses make it possible for us to understand the apparent lack of ionization losses of medium and heavy nuclei in interstellar space[13] by noting that most of the particles observed at low energies originate at higher energies where ionization losses are negligible.

* Research supported by NASA Grant NGL-21-002-033. Present address: Department of Environmental Sciences, Tel-Aviv University, Ramat-Aviv, Tel-Aviv, Israel.

+ NAS-NASA Resident Research Associate

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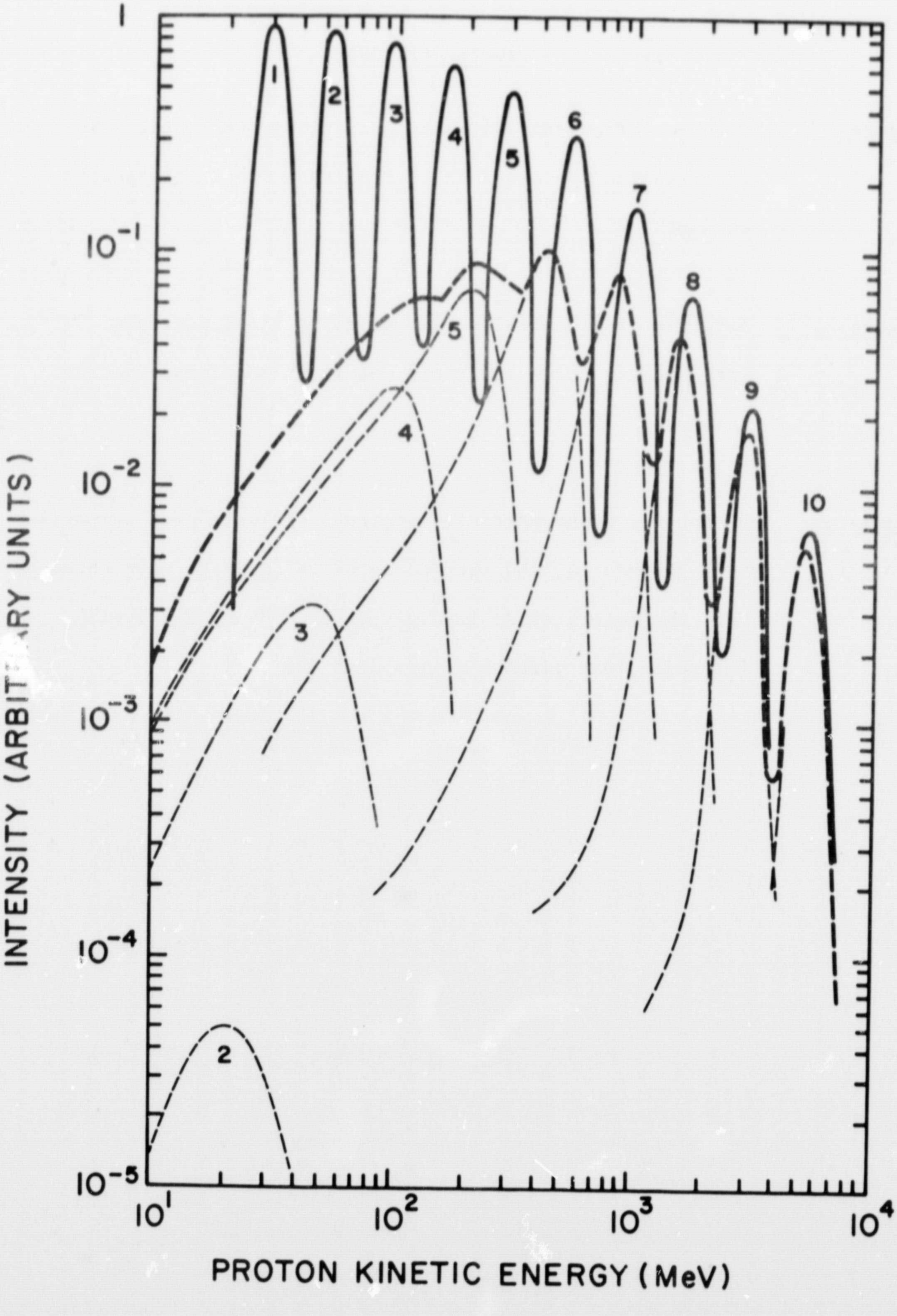
FIGURE CAPTIONS

Figure 1. A series of essentially monoenergetic proton spectra in interstellar space and their resultant modulated spectra at earth.

Figure 2. A series of essentially monoenergetic alpha particle interstellar space and their resultant modulated spectra at earth.

Figure 3. Proton and alpha particle spectra. The data were summarized in Reference 14, and the modulated intensities were obtained from the interstellar intensities by solving Eq. 1 with interplanetary parameters given in the text.



INTENSITY (ARBITRARY UNITS)
PROTON KINETIC ENERGY (MeV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{1}
10^{2}
10^{3}
10^{4}
1
2
3
4
5
6
7
8
9
10
5
4
3
2

FIGURE 1

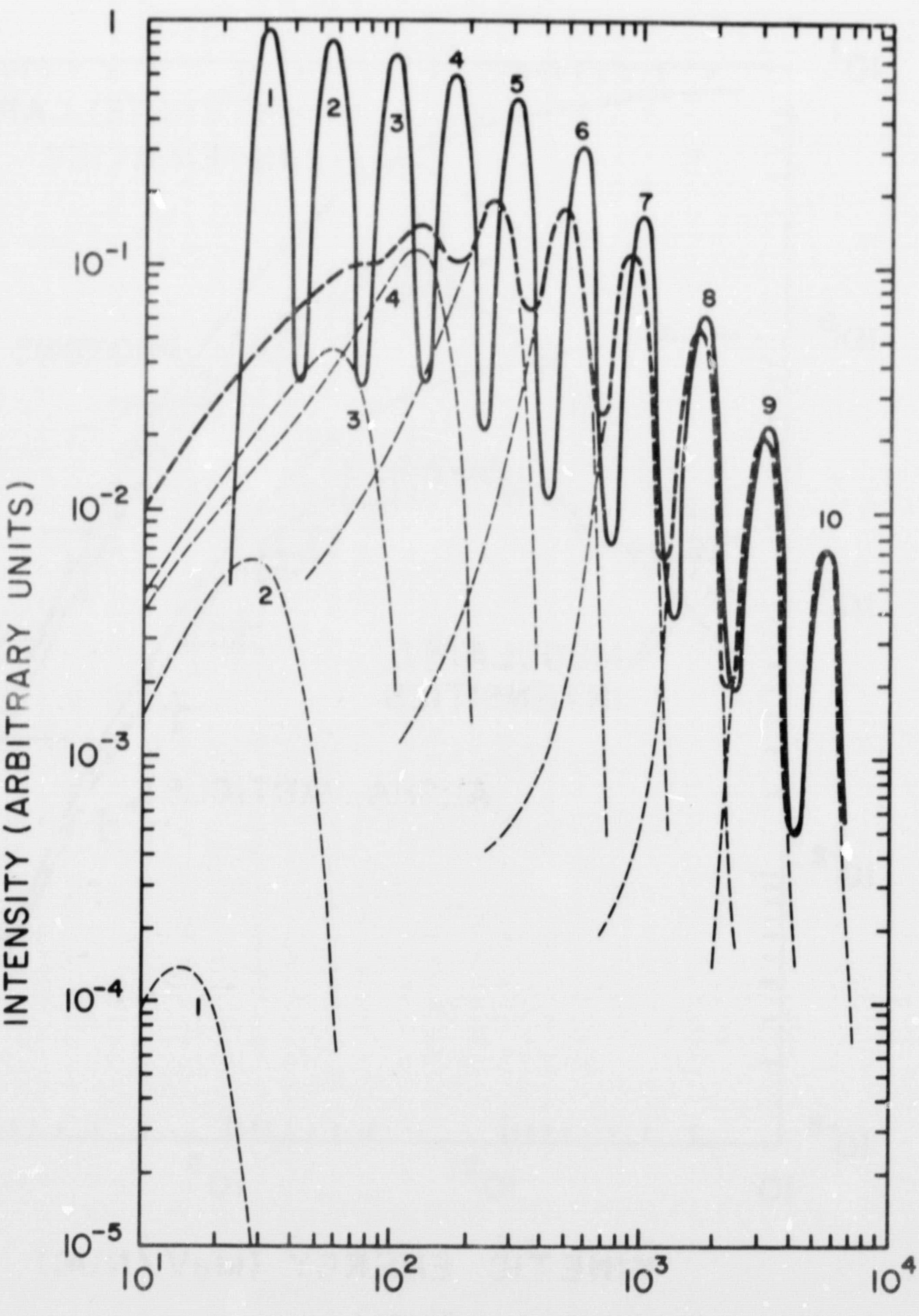
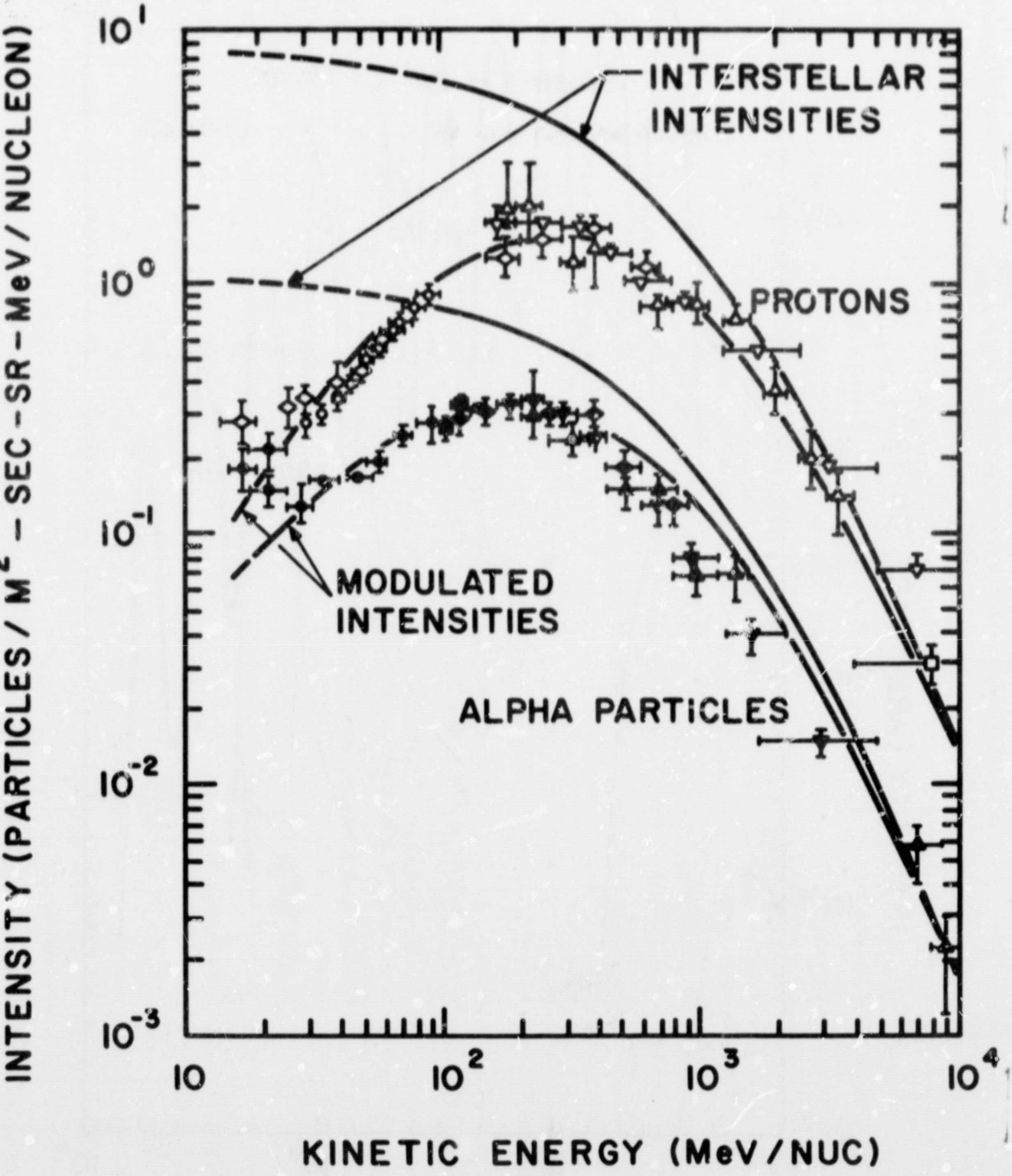

1
10^-1
10^-2
10^-3
10^-4
10^-5
10^1
10^2
10^3
10^4
INTENSITY (ARBITRARY UNITS)
KINETIC ENERGY (MeV/NUC)
1
2
3
4
5
6
7
8
9
10
4
3
2
1

FIGURE 2



INTENSITY (PARTICLES / M^2 - SEC - SR - MeV / NUCLEON)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
INTERSTELLAR
INTENSITIES
PROTONS
MODULATED
INTENSITIES
ALPHA PARTICLES
10
10^2
10^3
10^4
KINETIC ENERGY (MeV / NUC)

FIGURE 3